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Direct optical measurement of vorticity in fluid flow

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Even though vorticity is one of the most important variables in fluid dynamics, we do not currently have a practical way to measure it directly and in a non-intrusive fashion. In this exploratory research effort we demonstrate the first direct and localized non-intrusive measurement of vorticity in a fluid flow using the Rotational Doppler Effect (RDE) and Laguerre-Gaussian (LG) light beams that possess orbital angular momentum (OAM). The approach has been implemented in the flow field of solid body rotation where the flow vorticity is known precisely. Experimental results are found to be in excellent agreement with the expected values.

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Direct Optical Measurement of Vorticity in Fluid Flow

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I. Background

Vorticity is mathematically defined as the curl of the velocity vector, $\boldsymbol{\Omega} = \nabla \times \boldsymbol{U}$, and is physically interpreted as twice the local rotation rate (angular velocity) of a fluid particle $\boldsymbol{\omega_f}$, i.e. $\boldsymbol{\Omega} = 2\boldsymbol{\omega_f}$. It is a flow variable that is fundamental to the basic physics of many areas of fluid dynamics, including the field of aerodynamics, turbulent flows, chaotic motion, and many others. Even though spatially- and temporally-resolved direct measurement of instantaneous vorticity has been a long-held goal, it has proven elusive to date. Currently in all non-intrusive methods, whether particle-based such as Laser Doppler Velocimetry (LDV) and Particle Image Velocimetry (PIV) [1] or molecular-based as in Molecular Tagging Velocimetry (MTV) [2], vorticity is estimated from a number of velocity field measurements at several points near the point of interest, which then allow computation of the velocity derivatives over space and therefore the curl of the velocity vector. These methods provide a measurement of vorticity that is spatially averaged over the (small) spatial resolution area of each method. The first direct measurement of vorticity was attempted more than three decades ago by measuring the rotation rate of planar mirrors embedded in 25μm transparent spherical beads that were suspended in a refractive-index-matched liquid [3]. This method has rarely been utilized since its implementation is very complex and the required index matching significantly limits its use and prohibits its application in gas (air) flows. In fluid dynamics we do not currently have a way to directly measure $\boldsymbol{\Omega}$ in a non-intrusive manner with high spatial and temporal resolution, even at a single point.

Direct non-intrusive measurement of vorticity requires a laser-based method that is sensitive to rotational motion. Translational velocities can be measured with laser Doppler velocimetry (LDV) by taking advantage of the (linear) Doppler Effect, which causes a well-understood frequency shift that is perceived when objects move towards or away from a source of light. Analogously, but much less utilized, the Rotational Doppler Effect (RDE) can be used to measure the angular velocity of a rotating object [4-5]. Measuring with RDE requires the use of Laguerre-Gaussian (LG) light beams that possess orbital angular momentum (OAM) l , a spatial (azimuthal) modulation of the beam phase front. The use of LG laser beams with counter-rotating OAM ($\pm l$) to determine the angular speed of rotating objects based on RDE was recently reported by Lavery et al. [6]. When the illumination comprises two helically phased beams of opposite values of l, their scattering into a common detection mode gives opposite frequency shifts resulting in an intensity modulation of frequency $f_{mod} = 2|l|\omega/2\pi$, where ω is the angular velocity of the rotating object. With this type of setup Lavery et al. [6] were able to measure the angular velocity of a spinning disk. The same concept was later employed to measure the angular velocity of a microparticle trapped and spinning in an optical trap [7].

II. Objectives

We believe it is now possible to achieve the long-held goal of direct vorticity measurement by using rotational Doppler to measure the angular velocity of microscopic seed particles, much the same way that the familiar linear Doppler Effect is used in laser Doppler velocimetry (LDV) to measure the translational velocity of seed particles. In this exploratory effort, our objective is to demonstrate the feasibility of direct vorticity measurement in fluid flow at a single point with RDE using LG laser beams with counter-rotating OAM.

III. Experimental Setup

These experiments are aimed at vorticity measurements in a fluid flow based on angular velocity measurement of micron sized particles free flowing in the fluid. Very small particles faithfully track the fluid flow and, after steady state is reached, they move with the local flow speed and rotate with the local angular velocity of the fluid (or half the local flow vorticity at the particle center) [8]. We demonstrate the new vorticity measurement technique in the simple flow field of solid body rotation where the vorticity field of the flow is well characterized and known theoretically. Two sets of experiments are presented. In the first, the signal from a group of 6 µm microparticles is integrated to obtain the average fluid rotation rate about the beam optical axis within a 100 micron illumination region, and therefore, the spatially-averaged average vorticity within that region. In the second experiment, the same information is obtained by measuring the angular velocity of a single 100 µm particle in the flow.

The optical setup is shown in Figure 1(a). A 488 nm continuous wave light from an optically pumped semiconductor laser (Genesis MX, Coherent, USA) with initially Gaussian beam profile is expanded by a telescope (L1,L2) and reflected off a phase-only two-dimensional liquid crystal on silicon spatial light modulator (LCOS-SLM, Hamamatsu, Japan). The SLM is programmed with a diffraction pattern shown in Figure 1(b). The reflected light possesses an orbital angular momentum with a combination of topological charges ± 18 and its far-field intensity profile corresponds to a circular periodic structure with 36 petals (Figure 1(c)). The beam is then focused with long focal length lens L3 and first diffraction order containing desired spatial mode is selected with an aperture. Lens L4 recollimates the beam, which after reflection from dichroic mirror (DM) is focused by lens L5 (60mm focal length) into the center of a rotating cylindrical container with the beam optical axis aligned along its rotation axis. The beam diameter at the focus is measured to be about 120 µm. The container is filled with fluorescent micro-particles suspended in a density matched solution of water and glycerin (density about 1.05). Two sets of red fluorescent polymer microspheres (Thermo Fisher Scientific Inc.) are used in these measurements, one with 6 µm diameter (15% variance) and the other 100 µm diameter (7% variance). The use of fluorescent microspheres allows us to reject all scattered signal from the rotating surfaces of the container and guarantee the measured signal originates from within the rotating body of fluid. The container cap is fitted with a thin quartz window that touches the liquid surface at all times to eliminate free surface effects. The angular velocity $\boldsymbol{\omega}$ of the container is controlled by a motor (3501 Optical Chopper, New Focus, USA) with an accurately known rotation frequency f and, therefore, a well-prescribed container angular velocity $\boldsymbol{\omega} = 2\pi f$. Measurements were done after the container was spun for a few minutes to ensure a steady state solid body rotation flow field had been established. The resulting flow field is devoid of any secondary flow and precisely characterized by the solid-body rotation velocity field $\boldsymbol{U} = \boldsymbol{r} \times \boldsymbol{\omega}$ and its spatially uniform vorticity field $\boldsymbol{\Omega} = 2\boldsymbol{\omega}$. Special care was taken to align laser beam axis with the axis of rotation for the fluid container.

Epi-directional (backward) fluorescent light from the irradiated particles is collected and focused onto a PIN photodiode. A small diameter pinhole is set before photodiode in order to spatially filter out signal coming outside of focal volume in fluid. Time series of intensity modulated signal are recorded at 10 KHz sampling rate and spectrally analyzed.

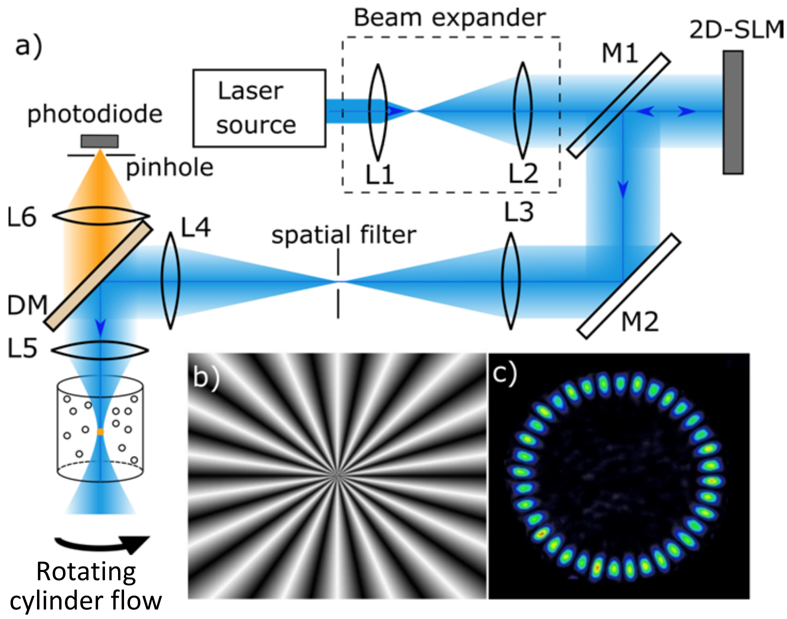

Figure 1. (a) Experimental setup. L1-L6, lenses; M1-M2, mirrors; DM, dichroic mirror.(b) Diffraction pattern displayed on 2D White color corresponds to 0 phase shift while black corresponds to 2π phase shift with 256 steps in between. (c) Resulting beam structure used to illuminate particles in fluid flow.

IV. Results & Discussion

For these measurements the LG laser beam has an OAM with $l = \pm 18$, resulting in 36 bright features (petals). Therefore, scattering from objects rotating at angular velocity $\boldsymbol{\omega}$ (or rotation frequency f) leads to intensity modulation at frequency $f_{mod} = 36\frac{\omega}{2\pi} = 36\,f$. The first set of data in Figures 2 and 3 shows the measurement with 6 µm fluorescent particles. In this case, by measuring the rotation rate of ensemble of particles within the ≈ 100 µm beam diameter we are obtaining the average fluid rotation rate within that region. Figure 2 shows examples of intensity modulation of collected (AC-coupled) signal for four different prescribed rotation frequencies of the cylindrical container. Fourier transform of each signal was taken to obtain the spectral information in Figure 3 using a short data record of about 200 ms in length.

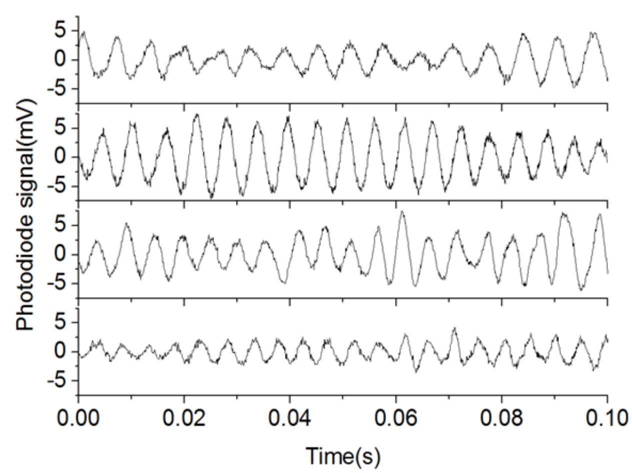

Figure 2. 100 ms long time series of collected signal for four different rotation frequencies of the cylindrical container: f = 4.28 Hz, 4.76 Hz, 5.24 Hz and 5.71 Hz.

From the spectral peaks in Figure 3 we measure the modulation frequencies for the four cases to be 154.16±5 Hz, 171.37±5 Hz, 188.58±5 Hz, and 205.76±5 Hz. These values correspond to the measured fluid rotation rates of 4.28±0.14 Hz, 4.76±0.14 Hz, 5.24±0.14 Hz, and 5.72±0.14 Hz, respectively.

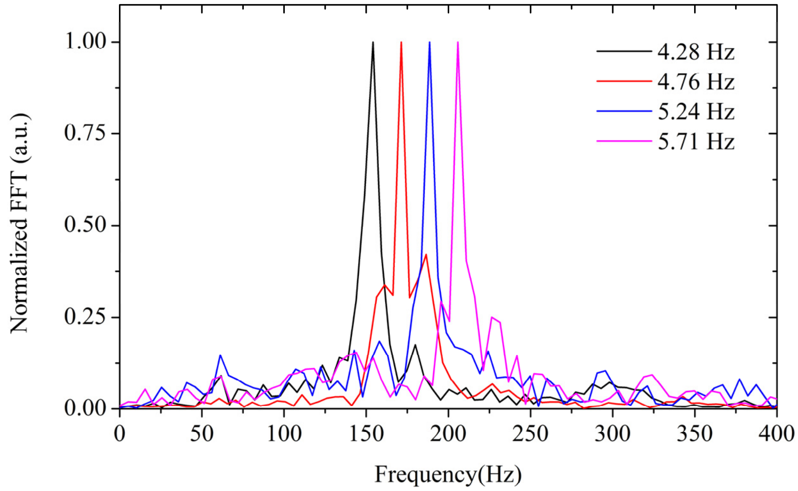

Figure 3. Power spectrum of signal for collection of 6 µm particles in solution (≈ 200 ms data record).

These values are in excellent agreement with the prescribed rotation frequencies of the rotating fluid container. Accuracy of these measurements is limited by FFT resolution of 5 Hz corresponding to the 200 ms data record that was used. Given the steady flow field in this experiment, one can improve the measurement accuracy, if desired, by increasing the length of the data record for FFT analysis.

The second set of experiments was carried on with larger 100 µm particles with low particle density in solution to ensure single particle measurement within the ≈ 100 µm beam diameter. This was confirmed by visually observing the single particle presence in the focal volume of structured laser beam based on its intensity time series during data collection. FFT analysis for two different prescribed rotation frequencies of the cylindrical container, $f =$ 4.28 Hz and 4.76 Hz, is presented in Figure 4. The peaks indicate modulation frequencies of 154.08±5 Hz, and 170.10±5 Hz for these two cases, where the FFT resolution of 5 Hz is, as before, dictated by the data record length (≈ 200 ms). The corresponding values of the measured fluid rotation rates are 4.28±0.14 Hz, 4.73±0.14 Hz, which are again in excellent agreement with the imposed rotation

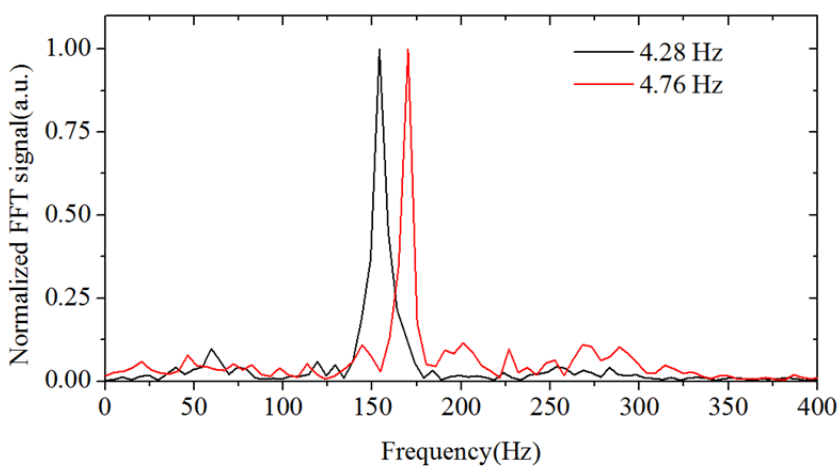

Figure 4. Power spectrum of signal for a single 100µm particle in solution for two different rotation frequencies of the cylindrical container: $f =$ 4.28 Hz, and 4.76 Hz (≈ 200 ms data record).

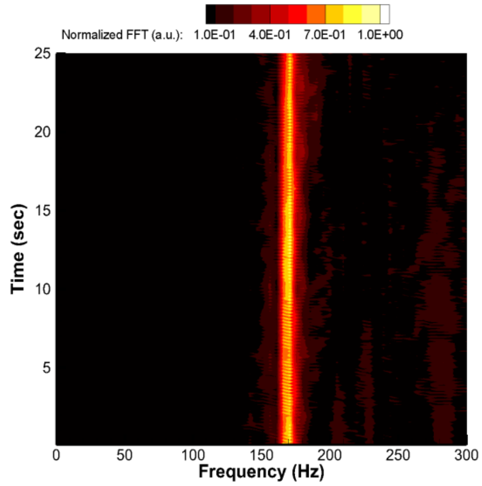

Figure 5. FFT map of signal for a single 100 μm particle in solution over time (f = 4.76 Hz)

frequencies of the rotating fluid container. As indicated before, the FFT resolution and hence the rotation rate measurement accuracy can be improved by using a longer data record, which is appropriate for this steady flow field where vorticity and fluid rotation rate do not vary in time. Figure 5 shows a map of the time evolution of 200ms window FFT for the cylinder rotation frequency of f = 4.76 Hz. Only a 25s segment of a longer 40s record is depicted in this figure. The steady nature of the flow is confirmed by the time invariant spectral peak in Figure 5 over a long period of time, during which the 100 μm particle lingers inside the laser beam at the axis of the rotating container while spinning with the fluid rotation rate. Measuring the spectral peak based on the 40s data record yields a modulation frequency of 171.5±0.025 Hz, or particle/fluid rotation rate of 4.76, in perfect agreement with the imposed rotation frequency of the fluid container.

The solid body rotation flow field was selected for these proof-of-concept experiments because it is relatively simple to create and has well-characterized velocity and vorticity fields. When the liquid-filled cylindrical container initially at rest starts to spin, the fluid layer near the moving wall starts to move with the cylinder due to the no-slip viscous boundary condition at the wall. The motion is then propagated throughout the container by viscous shear until the entire body of liquid rotates at the same speed of the container. The final steady state velocity field is that of solid body rotation with vorticity that is constant in time and uniform in space, with axis parallel to the axis of rotation of cylinder and magnitude equal to twice the cylinder angular velocity. While we have demonstrated here the idea of vorticity measurement using laser beams with OAM in a steady flow environment, clearly most exciting applications would be in unsteady flows. For micro particles in Stokes flow regime, particle rotation time response can be estimated from $\tau = \frac{\rho_p\, d^2}{60\mu}$, where ρ_p and d are the particle density and diameter, and μ is the fluid viscosity [9]. For the 100 μm particle in our experiment the response time is about 100 μsec. Therefore, unsteady vorticity measurements are also feasible. Because of the quadratic dependence of particle time response on diameter, one can select the appropriate particle size to ensure a response time that is faster than the flow fluctuation time scale.

While the experiments we have reported here represent the extension of the work of Lavery et al. [6] to the field of fluid dynamics, there are certain differences between the two as well. In the latter, the scattering signal originates from the planar surface of a spinning disk. In ours, measurements are carried out within the body of the fluid and the scattering signal is from a finite volume inside the fluid. For measurements with high spatial resolution, this scattering volume needs to be localized to a small region. In the current experiments, this was achieved by focusing the laser beam to about 100 µm diameter inside the liquid container.

V. Summary

We have demonstrated the first direct and localized non-intrusive measurement of vorticity in a fluid flow using the Rotational Doppler Effect (RDE) and Laguerre-Gaussian (LG) light beams that possess orbital angular momentum (OAM). The approach has been implemented in the flow field of solid body rotation where the flow vorticity is known precisely. In one experiment measurements with a group of 6 µm microparticles is used to obtain the average fluid rotation rate about the beam optical axis within the 100 micron illumination region, and therefore, the spatially-averaged vorticity within. In another experiment, the same information is obtained by measuring the angular velocity of a single 100 µm particle in the laser beam. In both experiments the measured results are in excellent agreement with those expected from the prescribed rotation frequencies of the rotating fluid container.

Although, the technique is demonstrated here in a simple flow where vorticity is uniform and steady, the approach holds great promise for unsteady flows with spatially varying vorticity field. We plan to explore extensions of this measurement technique to more complex flow environments.

VII. Publications

Conference Publications –

Anton Ryabtsev, Shahram Pouya, Manoochehr Koochesfahani and Marcos Dantus, "Characterization of vorticity in fluids by a spatially shaped laser beam," *Proc. SPIE* 9343, Laser Resonators, Microresonators, and Beam Control XVII, 93431G (March 3, 2015); doi:10.1117/12.2080238; http://dx.doi.org/10.1117/12.2080238

Journal Manuscript in Preparation –

The following manuscript will be submitted for publication in December 2015.
“Fluid flow vorticity measurements using laser beams with orbital angular momentum,” by Anton Ryabtsev, Shahram Pouya, Alireza Safaripour, Manoochehr Koochesfahani, and Marcos Dantus.

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7. Phillips, D. B., Lee, M. P., Speirits, F. C., Barnett, S. M., Simpson, S. H., Lavery, M. P. J., Padgett, M. J., and Gibson, G. M., "Rotational Doppler velocimetry to probe the angular velocity of spinning microparticles." *Physical Review A*, **90**, 011801(R) (2014).
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FA9550-14-1-0312

Principal Investigator Name
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Abstract

Even though vorticity is one of the most important variables in fluid dynamics, we do not currently have a practical way to measure it directly and in a non-intrusive fashion. In this exploratory research effort we demonstrate the first direct and localized non-intrusive measurement of vorticity in a fluid flow using the Rotational Doppler Effect (RDE) and Laguerre-Gaussian (LG) light beams that possess orbital angular momentum (OAM). The approach has been implemented in the flow field of solid body rotation where the flow vorticity is known precisely. Experimental results are found to be in excellent agreement with the expected values.

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Extensions granted or milestones slipped, if any:

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Reporting Period

Laboratory Task Manager

Program Officer

Research Objectives

Technical Summary

Funding Summary by Cost Category (by FY, $K)

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